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U.S. DEPARTMENT OF THE NAVY  
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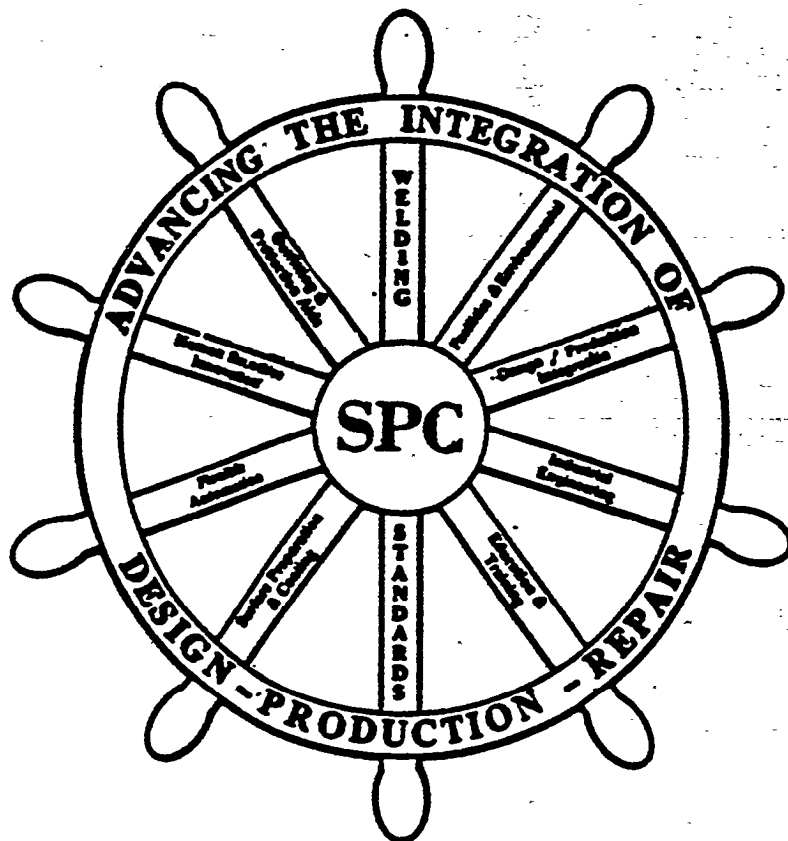
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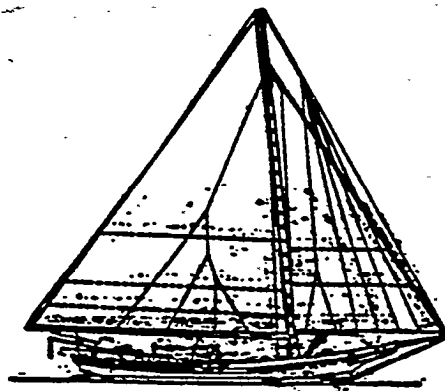
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# THE NATIONAL SHIPBUILDING RESEARCH PROGRAM 1988 SHIP PRODUCTION SYMPOSIUM

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# Electroslag Surfacing: A Potential Process for Rebuilding and Restoration of Ship Components No.11A

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## ABSTRACT

With construction of new commercial ships in U.S. shipyards at an all-time low and Congressional appropriations insufficient to maintain a U.S. fleet of 600 ships, the priorities of the surviving U.S. shipyards are changing from that of shipbuilding to ship rebuilding, restoration and repair.

This paper presents a review of the international literature on the most recent developments in thick section surfacing by electroslag surfacing (ESS) using strip or wire electrodes. The advantages of this newly-developed technique from Japan are explained in comparison with the conventional surfacing processes, such as submerged arc surfacing (SAS). A number of innovations and applications in this area are introduced to emphasize the substantial economical advantage of strip ESS for ship repair and manufacturing.

ESS with strip electrodes is capable of overlaying a wide variety of corrosion and/or wear-resistant deposits on structural ship components with half the dilution level and twice the deposition rate of its closest competitor, SAS. Because of its significant economical merits, strip ESS has already become the dominant thick-section surfacing process in many industrialized countries, particularly in Japan, the Soviet Union and parts of Europe.

## NOMENCLATURE

ESS -- Electroslag Surfacing  
ESW -- Electroslag Welding  
ESR -- Electroslag Remelting  
SAS -- Submerged Arc Surfacing  
SMAW -- Shielded Metal Arc Welding  
GMAW -- Gas Metal Arc Welding

## INTRODUCTION

The future requirement for new Ships forecast by the Association of West European Shipbuilders (1) implies over a third of the world's shipyard

capacity active in 1985 will have to close if it is to be brought into line with demand. The Japanese shipbuilders have tried to maintain their capacity to meet the predicted market upturn in the early 1990's. The south Korean shipbuilding industry has flourished since 1978, and a concerted sales drive is presently under way to utilize as much capacity as possible.

Unfortunately, international competition and foreign labor rates have put virtually all commercial shipbuilding contracts out of reach for U.S. shipbuilders (2,3). This has created a fiercely competitive environment for the dwindling U.S. Naval contracts. With construction of new commercial ships in U.S. shipyards at an all-time low and Congressional appropriations insufficient to maintain a U.S. fleet of 600 ships (4), the priorities of the surviving U.S. shipyards are changing from that of shipbuilding to that of ship rebuilding, restoration and repair.

Various surfacing processes have been utilized to repair and rebuild corroded or worn ship components. The near-future need for more economical repairing methods must be increasingly emphasized in order to remain competitive internationally. Surfacing by the Shielded Metal Arc Welding (SMAW) and Gas Metal Arc Welding (GMAW) techniques are labor intensive with little opportunity for innovation and improvement. For many years, SAS with strip electrodes was considered the most cost-effective method to overlay large components, such as ship propeller shafts, and now still prevails in the United States. The Japanese and Soviet shipbuilders, in particular, have developed highly cost-effective methodologies to rebuild large ship components using an innovative concept known as "Electroslag Surfacing". Strip ESS exhibits substantial advantages over strip SAS in the areas of "recess control, surfacing quality and economic productivity. It has completely replaced the less economical surfacing methods in

Japan and the Soviet Union, but has yet to be "discovered" in U.S. shipyards and manufacturing industries. In fact, except for the current program sponsored by the National Coastal Research and Development Institute at the Oregon Graduate Center, virtually none of America's manufacturing and shipbuilding industries have benefited from this new technology.

Due to the relative newness of ESS, the terminology throughout the world varies. For example, ESS is commonly referred to as (1) resistance electrosag surfacing, (2) electrosag overlay welding, and (3) electrosag cladding. The "strip" term is often added into these terminologies because filler metals are commonly utilized in the form of strip material.

In 1980, Kawasaki Steel (5) of Japan first developed a reliable strip ESS process and registered several patents in the Western world. This technique rapidly spread throughout Japanese industries (6). Several western European countries also adopted this process and are commercially manufacturing standard ESS equipment.

For the last seven years, a great number of innovations in ESS have been developed. However, it is surprising that strip ESS had not caught on in American industries. In 1985, Forsberg of Sandvik Steel published the first article about this technique in an American journal (7). Since that time, the manual, semi-automatic and SAS methods continue to dominate virtually all overlaying applications in the United States.

The purpose of this study is to critically review the international literature on ESS and strip ESS. Of particular emphasis will be the flux chemistries and the electrochemical reactions that are associated with this processing innovation. The advantages of surfacing with the strip ESS method will be reported. Also included will be the results of preliminary studies on strip ESS for practical applications on ships currently underway at Oregon Graduate Center.

#### CHARACTERISTICS OF ELECTROSLAG SURFACING

Although the strip ESS process is new, the fundamental principle of ESS is similar to that of the Electrosag Welding (ESW) and Electrosag Remelting (ESR) processes. Heat is generated by ohmic heating of a resistive slag by the passage of an electric current through a strip electrode, which is continuously fed into the molten slag pool. Figure 1 shows a schematic diagram of the ESS process.

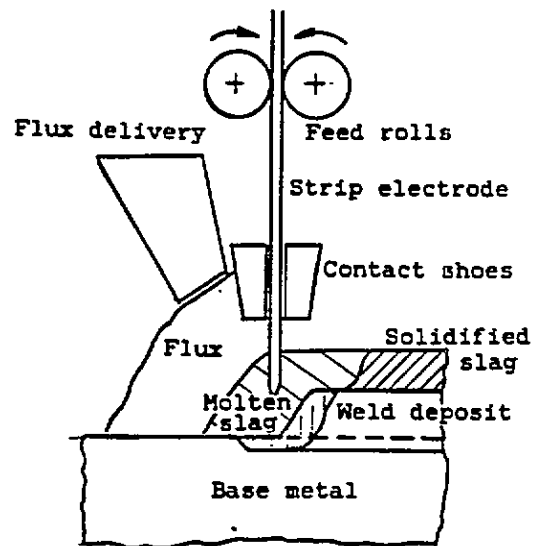


Fig. 1 Diagram of the Electrosag Surfacing process

Considerable differences in process detail exists between ESW and ESS. These include:

- (1) Welding position in ESW is vertical or near-vertical, whereas ESS is performed in the flat position:
- (2) The depth of slag pool and base metal dilution are substantial in ESW, whereas ESS requires only a shallow slag pool and produces low dilution:
- (3) The chemical composition of electrodes in ESW are usually similar to that of the base metal, whereas in ESS, they may (or may not) be substantially different; and
- (4) Travel speed in the ESS process is about 10 to 15 times greater than conventional ESW.

The process appearance of strip ESS is nearly identical to that of strip SAS, except SAS is primarily arc-functioning while ESS is generally arcless and produces heat by I<sup>2</sup>R (ohmic) heating of the molten slag. However, strip ESS exhibits a series of advantages over strip SAS in providing low dilution deposits, high deposition rates and better productivity.

The first important feature of strip ESS is low dilution in the deposits. In any surfacing process, a critical factor requiring precise control is the dilution ratio. The term, "dilution ratio", is expressed as:

$$\% \text{ Dilution} = B / (A + B) \times 100$$

where A is the cross sectional area of reinforcement of deposits above the

base metal surface, end B is the cross sectional area of the melted base metal below the workpiece surface. In terms of surfacing, it is necessary to keep low dilution levels because the surfaced layer has to maintain its desired inherent properties, like wear the Corrosion resistance. In SAS, the arc tends to penetrate more deeply and melt more base metal in comparison to ESS. For example, the strip SAS process typically produces a dilution ratio of 18% at a current density of 25 A/mm<sup>2</sup> (16.1 kA/in<sup>2</sup>), compared to approximately a 9% dilution ratio for the strip ESS process at 41 A/mm<sup>2</sup> (26.5 kA/in<sup>2</sup>) (8). Thus, the chemical composition of the overlay deposited by ESS will more closely resemble that of the filler metal.

The second important feature of ESS is its high deposition rate, which is a function of the current density. The use of a high current density in the SAS process will effectively make the arc hotter and stiffer, thus causing it to penetrate more deeply into the workpiece to increase the dilution ratio. On the other hand, the strip ESS process allows the use of almost double the current density to produce a much higher deposition rate while still maintaining a lower dilution level. This desirable combination of a high deposition rate and a low base metal dilution was the main incentive for Japanese industries to eliminate SAS in favor of ESS.

The third important feature of ESS is the feasibility of single layer deposition. By virtue of its low dilution and high deposition rate, surfacing can be most economically attained for the desired thickness of a corrosion or wear resistant layer with a designed chemical composition. Since the dilution level for strip ESS is almost half that of strip SAS, the strip ESS process can more likely eliminate the necessity for multiple layer deposits and result in greater cost effectiveness. Furthermore, thin overlays (about 3 mm or 1/8 in. thick) are far more advantageous by ESS because dilution decreases with overlay thickness for ESS but increases by SAS.

Further economical advantage is gained by the use of wide strip which deposits a greater surface area per unit time. Large strip widths (> 60 mm 12.4 in.) are particularly more difficult to apply by SAS than ESS. In SAS process, the arc is struck at one corner of the strip and then starts traversing the entire width of the strip (5.9). The strip is consumed by the oscillatory movement of the arc across the strip. However, in ESS the strip is consumed uniformly across its entire width. This phenomenon is

illustrated in Figure 2 (5). The movement of the arc in SAS is not necessarily uniform and leads to inconsistent penetration and lack of fusion. For this reason, SAS has been limited to a strip width of 75 mm, whereas using strips as wide as 300 mm (11.8 in.) is not uncommon in ESS. A comparison between the strip ESS and SAS process is presented in Table I.

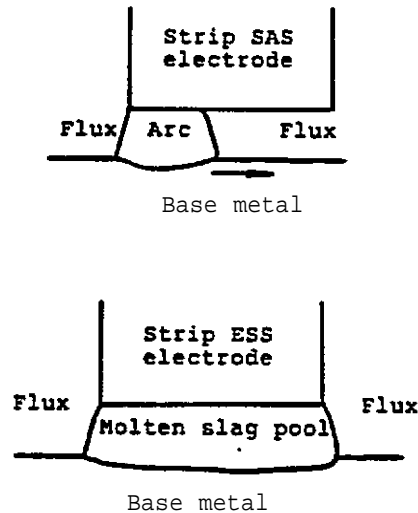


Fig. 2 Penetration characteristics of SAS and ESS

#### FURTHER INNOVATIONS IN ESS FROM JAPAN

##### External Magnetic Field for ESS

In 1980, Nakano and his colleagues in Japan (5) first developed an electromagnetic controlled strip ESS method called the MAGLAY process. During surfacing with wide strips (> 60 mm [2.4 in.]), the formation of undercutting and lack of fusion defects were found to be related to the flow pattern of molten slag and metal, which is driven by the electromagnetic force induced by the high values of the surfacing current. Electric current, flowing parallel from the strip to the bottom of the molten pool, makes both slag and metal move from the edges of the pool toward the center as illustrated in Figure 3. To counteract this force in the MAGLAY process, two direct current coils are mounted adjacent to the edges of the strip electrode resulting in counterbalancing magnetic forces. The use of an external magnetic field effectively (a) avoids undercut tie-ins, (b) eliminates slag entrapment, and (c) produces a more uniform thickness of overlay.

The MAGLAY process was patented in both Japan and Europe, and adopted as

Table I Comparison between submerged arc surfacing and electroslag surfacing with stainless steel strip electrodes (6)

	SAS	ESS
Strip: dimension (mm)	60 x 0.5	60 x 0.5
carbon content (%)	0.015	0.015
Parameters: I (A)	750	1250
v (V)	26	24
v (cm/min)	10	16
Current density (A/mm <sup>2</sup> )	25	41.7
Heat input (KJ/cm)	117	112.5
(KJ/cm <sup>2</sup> )	19.5	18.7
Bead thickness (mm)	4.5	4.5
Dilution (%)	16	9
Deposition rate (Kg/h)	14	22
Flux consumption	0.65	0.5
Carbon content of single deposit layer (base metal: 0.18% C)	0.045	0.030

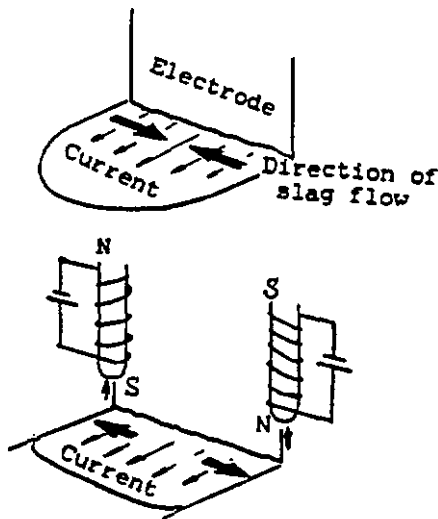


Fig. 3 Mechanism for eliminating undercutting by use of an external magnetic field (5)

the classical method of strip ESS in Europe and in many other countries. The strip-feeding head made by Soudametal (Belgium), which is now commercially available in the United States, employs a magnetic stirring device similar to the NAGLAY design.

#### "PZ" Arc-Facilitating Process

Strip surfacing at the Japan Steel Works also utilizes the electroslag mode of deposition but without the aid

of magnetic devices (6). Their process is called "PZ" and is illustrated in Figure 4. The important feature of

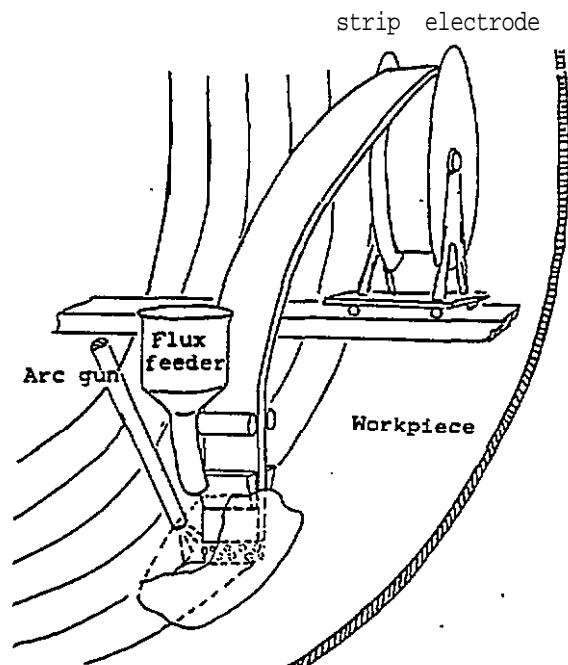


Fig. 4 PZ welding operation using 150 mm wide stainless steel strip (6)

this process is that an arc is always maintained at the strip extremities while most of the strip tip is still in the electroslag mode. The auxiliary arc facilitates bead tie-in and penetration, but avoids excessive dilution at the center of the bead caused by the Lorentz force. The 150 mm (6 in.) wide strips used in the "PZ" process provide a uniform overlay surface and a low dilution level in each bead.

#### "HS Process"

Kobe Steel Ltd. developed the high speed overlay welding technique called the HS Process (High Speed Strip Overlay Welding Process) which utilizes a strip that can be applied to an actual vessel even as a single layer process [10]. In terms of efficiency, the ES technique is claimed to utilize only a 75 mm (3 in.) wide electrode but competes attractively with the ordinary ESS process using a 150 mm (6 in.) wide electrode.

The key points of this technique are a high travel speed and a forward electrode inclination angle. usually when the electrode travel speed exceeds 200 mm/min (7.8 in/min), the electrical transfer through the slag pool shifts from electroslag to submerged arc due to an increase in slag resistivity with decreasing slag superheating. The inclination angle of the electrode permits molten metal to enter the gap between the base metal and electrode and produces a buffer by preventing deep penetration into the base metal, and reduces the dilution of the surfacing layers.

#### INNOVATIONS IN THE SOVIET UNION

The ESS process is also widely used in the Soviet Union and Eastern Europe. A great amount of innovations were frequently reported in their technical journals. Although most articles are often lacking technical details, their basic designs and functions could still be reviewed.

#### Multi-Strip Feeding

The Paton Welding Institute started studies on ESS with two electrode strips in the late 1970's. This method was virtually unknown in the West but was widely used in the Soviet Union and the Eastern European countries (11-13). When two strips are arranged as in Figure 5, the molten slag may rise between the two strip electrodes and directly contact with air, causing considerable convectional agitation. Thus, the distance between two strips has become another important parameter to be taken into account.

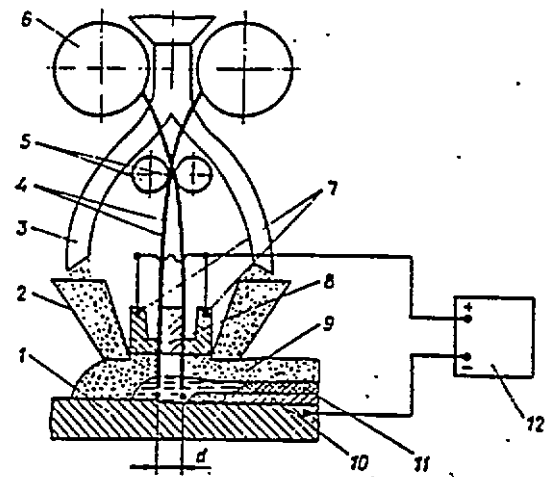


Fig. 5 Diagram illustrating deposition with two strip electrodes: 1) parent metal, 2) flux funnel, 3) flux feed guide, 4) strip electrodes, 5) feed roller, 6) spool, 7) current conducting jaws, 8) separator, 9) flux, 10) deposited metal, 11) slag, and 12) power source (12)

ESS with more than two wire electrodes has also been reported by V. Melikov (14). As many as 15 stainless steel electrodes (all 3 mm [1/8 in.] diameter **wires**) were simultaneously deposited over the entire width of the workpiece in the downhand position with artificial cooling. The low-carbon steel base plates were 70 mm (2.8 in.) thick, 500 mm (20 in.) long, and 340 mm (13.4 in.) wide.

A. Shyartser (15) claimed two hardfacing processes with a group of plate electrodes. In one case, the high Mn steel electrodes were deposited on worn dredger buckets. In another case, the high Cr casting iron electrodes were deposited on worn steel blades, as shown in Figure 6. The absence of cracks and formation defects made it possible to greatly increase the Service durability of hardfaced components and reduce the production cost. For example, tests on the blades showed that their wear resistance was virtually identical to that of those blades hardfaced by brazing expensive alloys, whereas the cost of the former was almost a factor of 8 lower.

#### Plasma-Electroslag Deposition

A plasma-ESS method was reported by A. F. Batakshev et al. (16) to deposit high purity copper on low alloy carbon steels, as shown in Figure 7. The requirement of an auxiliary plasma is to counteract the high conductivity of the copper overlay.

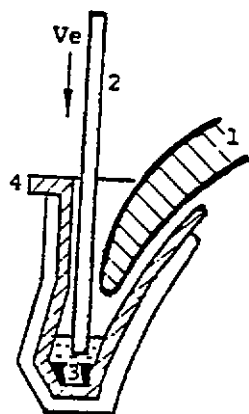


Fig. 6 The hardfacing of buckets:  
the diagram of the process 1) compo-  
nent, 2) electrode, 3) deposited metal,  
and 4) solidification mold (15)

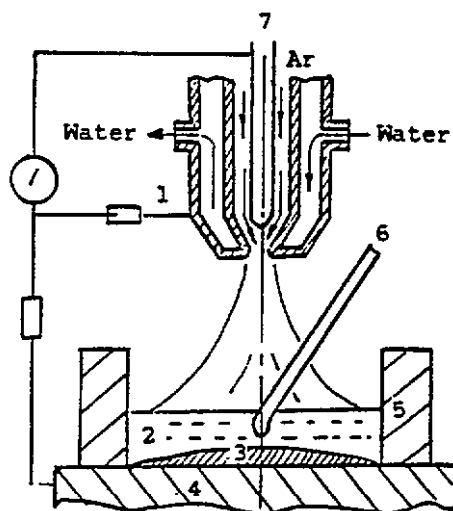


Fig. 7 Technological diagram of the  
plasma-ESS method (16): 1) plasma,  
2) slag pool, 3) deposit, 4) base  
metal, 5) shaping/cooling device,  
6) filler metal, and 7) electrode of  
plasma torch

In this process, the pilot arc is initially ignited in the plasma torch, followed by ignition of the plasma arc between the workpiece and the electrode of the plasma torch. A special flux is fed into the acting zone of the plasma jet. This flux contains elements with low ionization potentials (Ca, Na, Be, etc.), which increase the stability of the plasma jet due to a decrease in electrical resistance. The flux soon melts and forms a slag pool. When the base plate is heated to a sufficiently high temperature, the copper filler metal is fed into the slag pool, and the plasma torch and the mold are moved at the same time, resulting in the surface overlay.

The plasma ESS process provides a means to control the time dependence of heating the parent metal without the use of consumable electrodes. It also prevents contamination of the deposited copper. In a steady-state operation with the optimum parameters of 450-500A/55-60V and a 30-40 mm (1.4-1.6 in.) deep molten slag pool, the process could produce a 2-3 mm (0.1 in.) thick and 15-20 mm (0.6-0.8 in.) wide deposit in a single pass. The deposits of copper are free from pores, cracks and inclusions and contain no Si, W, Mn, and other commonly found impurities. The strength of bonding in the deposited metal is close to the strength of copper. The inventors (16) of this method claim that it could be used for repairing casting defects and hardfacing the surfaces of cutting tools.

#### Surfacing of Shaped Parts

A variety of examples could be found in the Soviet technical journals, reporting the use of ESS for the restoration of worn components having complex shapes. The surfacing of those shaped parts is performed by a modified electroslag welding process. A specially designed water-cooled mold is used to confine the molten slag and metal pool into the desired shape. Figure 8 illustrates the use of a shaped mold for surfacing the teeth of excavator buckets.

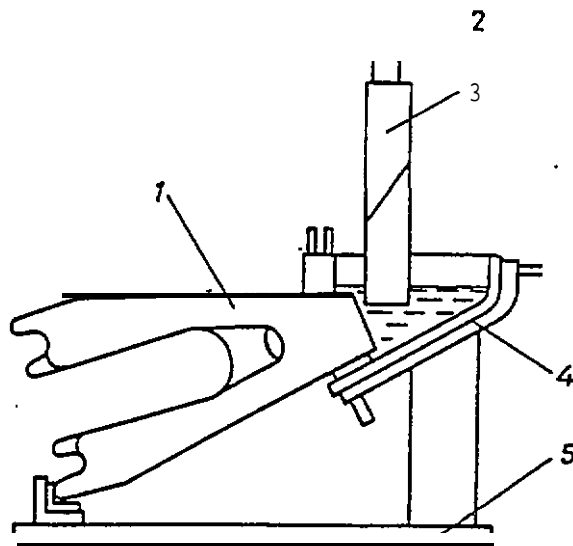


Fig. 8 Diagram illustrating the ESS  
of an excavator shovel tooth with  
varying chemical composition metal:  
1) tooth blank, 2) standard head,  
3) consumable electrode, 4) mold  
base, and 5) frame

As K. Valits indicated (17), to restore a complicated shape, the energy

of the melt must be sufficient to ensure both the transfer of the melt to the remote part of the mold end the complete fusion at that location. His experimental results verified that an increase in the voltage or the current density improved the quality of the deposited metal. However, when the current density was excessive, the slag pool could be "thermally saturated". The thickness of the deposited layer no longer increased, and the risk of short-circuiting was eminent.

For large-scale parts, the ESS operations were reported lasting more than 30 hours. To ensure a high quality of the deposited layer, the process must be stable and maintained without interruption. Stepanov (18) pointed out that the non-uniform adhesion of molten metal and the presence of a slag skull in long term ESS could cause rapid abrasive wear and local superheating in the tail part of the shaped mold. Thus, the inner surface of the mold has to be made of materials with high thermal conductivity and also high resistance to the action of molten slag and metal pools. In this case, copper and its alloys do not ensure the required thermal efficiency. He reported an application using a damping heat conducting layer in the solidification molds. The inner contact surface of the mold was made of a less thermally conductive alloy steel, followed by a damping heat conducting layer made of pure copper, and finally by the water-cooled structural steel base. This method provides proper control of the cooling rate of the deposited metal, and ensures a uniform temperature distribution in the molds.

#### Surfacing of Thin-Walled Components

Multi-electrode surfacing usually makes it possible to deposit, in a single pass, a layer of metal having the required thickness and width nearly equal to that of the components. Although its use for thin-walled components risks the possibility of burning through, a report from the Tashkent Institute of Railway Transport Engineers claimed the development of a successful example for the ESS of the friction wedge of the damper of wagons whose maximum wall thickness was only 5 to 6 mm (0.2 in.) (19), as shown in Figure 9.

In this process, nine electrode wires (each 3 mm [1/8 in.] in diameter) are deposited simultaneously, and an AC (not specified in that paper, but believed) power source with a hard external characteristic is used. The main parameters of this process include: 32 volts, an electrode feed rate of 0.51 m/hr (20 in/hr) and a surfacing speed of 1.8 m/hr (70 in/hr). A few factors

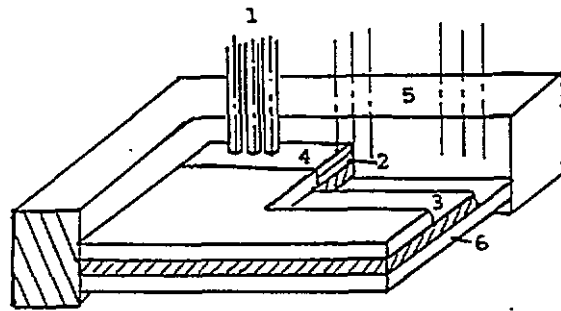


Fig. 9 Diagram of multi-electrode ESS of vertical surface of the friction wedge of the damper of a wagon:

1) axes of electrode, 2) slag pool, 3) metal bath, 4) flux, 5) copper shaping device, and 6) component (19)

are critical to prevent burn-through defects, including the slag pool depth, the electrode extension, and the stationary (without longitudinal displacement) feeding time of electrodes in the initial stage of surfacing for inducing the slag pool and the final stage of surfacing for filling the crater. By increasing the initial stationary feed time, the molten filler metal spread ahead of the electrode tip thermally protecting the base metal. A wear-resistant layer of 6-12 mm (0.24-0.47 in.) thick and 135 x 180 mm (5.3 X 7 in.) in size is reported being deposited in a single pass on the surface of mild steel.

#### surfacing Layers With Compositional Gradients

In many cases of service, the different portions of an individual hardfaced work piece experience different degrees of wear. The geometrical loss due to the uneven wear reduces its life prematurely. The rational solution to this problem is to make the working surface from composite metal, whose wear resistance changes gradually to accommodate the differences in the severity of wear at different locations on the workpiece. By producing a part that wears uniformly, the functional life of the part is lengthened.

Shyartser (20,21) developed a special surfacing process to provide a wear gradient for an excavator shovel, which is illustrated in Figure 8. In service, the abrasive wear on its rear face increased substantially from the tail end of a tooth to its apex. In order to extend its life, a prescribed variation in chemical composition of the deposited metal was obtained by depositing a special composite electrode which consisted of two dissimilar metals meeting along an inclined plane (Figure 10). In this case, the

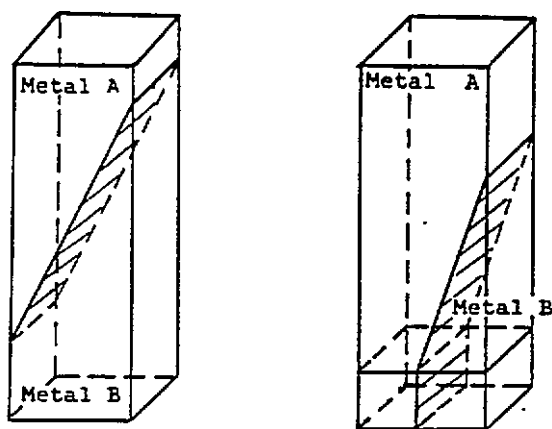


Fig. 10 Two composite electrodes designed to provide surfacing layer with compositional gradient (20,211

electrodes consisted of a high Mn steel and a high chromium iron. A calculation had to worked out for determining the combination ratio of electrode materials to obtain an overlay with the desired gradient in chemical composition. As illustrated in Table II, the surfacing deposits adjacent to the front face of teeth were a wear-resistant Cr iron, changing (towards the rear face) into a high Mn steel. In service, those hardfaced teeth maintained a consistent geometry (21).

Recently, Gulakov et al. (22) analyzed both the buffer effect of the weld pool and the element transfer from the base metal (or the previous deposited layer) on the final gradient of the chemical composition. They constructed a model of the molten surfacing pool and proposed ways of reducing the difference between the required and actual compositional

variation. A programming device was also designed to facilitate the gradient method of surfacing (23).

## PROCESS DETAILS

### Equipment

The strip feed rates required for the ESS process are within the ranges which characterize submerged arc wire welding and strip SAS. The equipment for strip SAS is essentially the same as that required for strip ESS (8), schematically illustrated in Figure 1. Thus, conventional DC constant voltage welding machines, capable of 1200 amps or more at 100% duty circle, can be easily converted to ESS by attaching a special strip feeding head. A few types of strip feeding heads are commercially available in European countries. Oerlikon provides a popular strip feeding head for strip electrodes in the width range of 50 to 125 mm (2 to 5 in.), which is made by Soudometal Company of Belgium.

The popular strip feeding head is basically an improved MAGLAY process device originally developed by Kawasaki Steel. The wheels and counterwheels provide pressure and guide the strip into the feeding nozzle. Both the pressure and the gap are adjustable to allow variation in the thickness of strips. A pair of magnetic solenoids are fitted along the sides of the strip feeding nozzle. The magnetic intensity of the solenoids can be adjusted separately by a control box to ensure the desired fluid flow characteristics of the overlay.

Direct current, constant voltage (DC-CV) power sources are recommended for ESS. Surfacing is always carried out using reversed polarity (the strip

Table II Variation in Chemical Composition and Mechanical Properties of Deposited Metal from the Front to the Rear Faces of Teeth Shown in Figure 8 (23)

specimen No.	Distance from Front Face mm (in.)		Content of %						HRC	Coefficient of Wear Resistance
			C	Cr	Mn	Si	Ni	Mo		
1	10	(0.4)	3.0	20	1.5	1.0	1.5	1.0	50	4.3
2	30	(1.2)	2.7	16	3.8	0.9	1.2	0.8	46	3.2
3	50	(2.0)	2.3	12	6.1	0.7	0.9	0.6	38	2.8
4	70	(2.8)	2.0	8	8.3	0.6	0.6	0.4	32	2.2
5	90	(3.6)	1.6	4	11.0	0.4	0.3	0.2	26	1.8
6	110	(4.4)	1.3	--	13.0	0.3	--	--	—	1.3

electrode is connected to the positive terminal of the power source) in order to ensure adequate fusion to the base metal. Since the optimal current density for ESS is around 40 A/mm<sup>2</sup>, the output rate of power sources at a 100% duty cycle should meet the following minimum load handling requirements: 1250A for 60 x 0.5 mm (2.4 x 0.02 in.) strips; 1800A for 90 x 0.5 mm (3.5 x 0.02 in.) strips; and 2400A for 120 x 0.5 mm (4.7 x 0.02 in.) strips (8). In practice, such high current levels are usually obtained by connecting two power sources in parallel.

#### Flux Chemistry

The flow of electrons in a surfacing or welding process may take place either through an arc or molten slag depending on the relative conductivity of the medium through which the electrons pass. In strip ESS, it is very critical to establish stable ohmic (arcless) conduction of electricity through a shallow slag pool of only about 20 mm (0.79 in.) depth. Other factors which are essential in ESS are the wettability of the slag, the bead profile, the slag removal, the recovery of alloying elements, and the reduction of gas generating components.

To maintain a stable electrosag mode through a shallow slag, a special flux composition had to be developed. Such fluxes must provide greater electrical conductivity than would be needed for normal electrosag welding of the same plate material. Adding large quantities of fluorides, mainly CaF<sub>2</sub> and NaF and/or semiconductors, such as TiO<sub>2</sub>, and FeO, can greatly raise the electrical conductivity of molten slag without risk of generating arcs. However, large quantities of TiO<sub>2</sub> in slag cause a deterioration in the detachability of the slag. Therefore, additions of fluorides are more preferable (8).

The level of electrical conductivity of slag is closely related to the fluoride content in the flux, as illustrated in Figure 11. The IIW (International Institute of Welding) Document XII-A-4-81 (24) described the effect of calcium and sodium fluoride additions on the electrical conductivity of the 3CaO-3SiO<sub>2</sub>-Al<sub>2</sub>O<sub>3</sub> ternary system, and indicated that when the fluorides were less than 40% (balance ternary), the submerged-arc mode prevailed; and when more than 50% fluorides, the electrosag mode prevailed. In terms of the electrical conductivity of the slag, this corresponded to a transition range of 2 to 3 n<sup>-1</sup> cm<sup>-1</sup>. Above 3 n<sup>-1</sup> cm<sup>-1</sup>, a stable electrosag mode is easily achieved. However, to restrict the generation of fluoride type gases (due to a reaction: 2CaF<sub>2</sub> + SiO<sub>2</sub> + 2CaO +

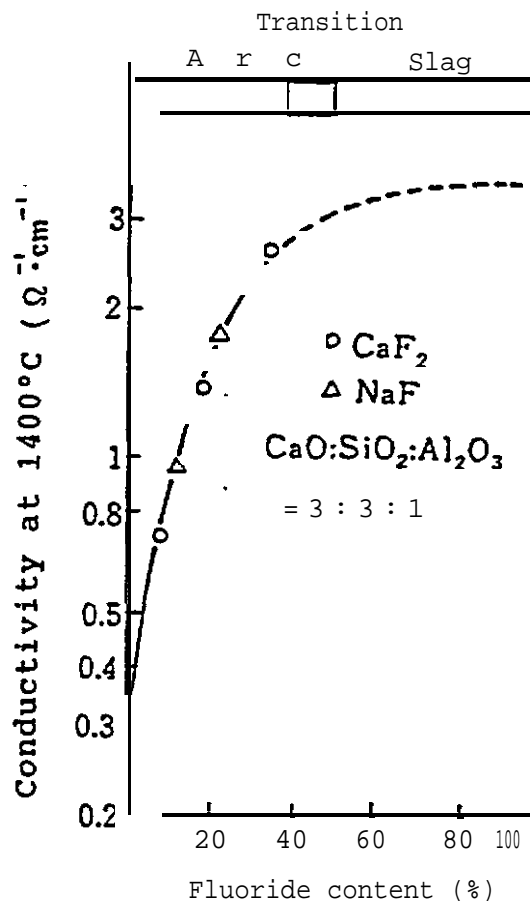


Fig. 11 Effect of fluoride content in flux on electrical conductivity and current conduction type during Strip ESS (24)

SiF<sub>4</sub>), additions of CaF<sub>2</sub> were usually held at slightly less than 50%.

In Japan, fluxes for stainless steel overlays are principally supplied by Kawasaki Steel and Kobe Steel (6). The Kawasaki XFS-150 is a fused flux with an electrical conductivity of about 3 n<sup>-1</sup> cm<sup>-1</sup> at 1700°C. It was patented in the United States in 1984 (25). The composition of Kawasaki's patented flux contains 50-60% CaF<sub>2</sub>, 10-20% SiO<sub>2</sub>, 5-25% CaO and 10-30% Al<sub>2</sub>O<sub>3</sub> in a ratio of SiO<sub>2</sub>/CaF<sub>2</sub> of at least 0.20 and a ratio of CaO/SiO<sub>2</sub> of at least 0.50.

In the Soviet Union, a series of fluxes were developed for ESS. The ANF series fluxes are of high fluoride contents (> 50%) and high electrical conductivities (26). The AN-series fluxes, which were originally used in ESW, are also used for the thick layer build-up. Their fluoride contents are below 25% and electrical conductivities are comparatively low (26). Some new fluxes were occasionally reported being

developed for certain special ESS processes (27). however, no concrete compositional information was presented.

In Western Europe, fluxes EST 122 and 201 are commonly used [8]. Some characteristic data of these two agglomerated fluxes are given in Table III. The flux EST 122 is specifically designed to be used for the depositions of all types of 300 and 400 series stainless steel strips. The flux EST 201 is designed for the deposition of the Ni-base alloys, such as 825, 600, 625 and 400 (7).

In the United States, the commercially available fluxes for ESS can be ordered through Sandvik Steel or Oerlikon, which are basically very close to those available in the European market. The Sandvik 375 welding flux is a universal flux for ESS (Table III). Its electric conductivity is 5 to 6 times greater than an ordinary submerged arc welding flux. It can be used to deposit corrosion-resistant cladding using 300 and 400 series stainless steel strip electrodes and certain hardfacing electrodes. Fluxes suitable for depositing nickel-base alloys are also available in the Sandvik series 17).

In a recent study (28) of ESS with stainless steel wire electrodes, fluxes of the  $\text{CaF}_2$ - $\text{CaO}$ - $\text{Al}_2\text{O}_3$  system were studied. It was noticed that at higher  $\text{CaF}_2$  percentages, (i.e. beyond 70%), the process was once again that of arc conduction. As the percentage of the  $\text{CaF}_2$  in the flux increased, there was a corresponding increase in the conductivity level. This, in effect, raised the current at the same wire feed speed, and gave rise to burn back problems. Hence, at higher  $\text{CaF}_2$  percentages, arcing could be visible on the surface of the molten slag. On the

other hand, below 40%  $\text{CaF}_2$ , the observed arcing was submerged-arc type as illustrated in Figure 12.

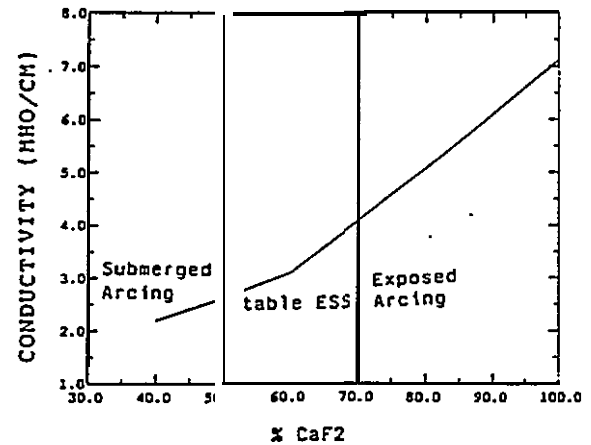
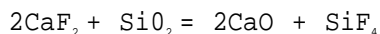


Fig. 12 Effect of  $\text{CaF}_2$  content in flux on electrical conductivity and current conduction mode during wire ESS (28)

Usually,  $\text{CaO}$ ,  $\text{SiO}_2$  and  $\text{Al}_2\text{O}_3$  are common additions for optimizing the conductivity level of a  $\text{CaF}_2$ -based flux. The practice at the Oregon Graduate Center (28) indicated that optimizing the viscosity level of molten flux is of the same importance. Since conductivity and viscosity have an inverse relationship, adjusting the flux composition becomes a complex problem.  $\text{SiO}_2$  is one compound which has a major influence on slag viscosity and slag flow (25). To maintain the desired viscosity, it is necessary to control a  $\text{SiO}_2/\text{CaF}_2$  ratio of at least 0.2 and to avoid evolution of toxic gases like  $\text{SiF}_4$  by the reaction:

Table III Fluxes Available From European Sources (7,8)

content	EST 122	EST 201	Sandvik 37S
(%) Alkaline & alkaline earth oxides ( $\text{CaO}$ , $\text{MgO}$ , $\text{K}_2\text{O}$ , $\text{Na}_2\text{O}$ )	50	50	50
(%) Amphoteric & alkaline earth oxides ( $\text{Al}_2\text{O}_3$ , $\text{TiO}_2$ , $\text{ZrO}_2$ )	25	25	25
(%) Silicon dioxide ( $\text{SiO}_2$ )	10 max	5 max	10
(%) Fluorides (expressed in F)	30	25	30
Flux density ( $\text{kg/dm}^3$ )	0.85	0.85	0.85
Flux consumption rate ( $\text{kg flux/kg strip}$ )	0.5	0.5	



In addition, as specified by the Kawasaki patent (25), the minimum requirement for CaO/SiO<sub>2</sub> ratio should be about 0.5 for stable ESS (Figure 13).

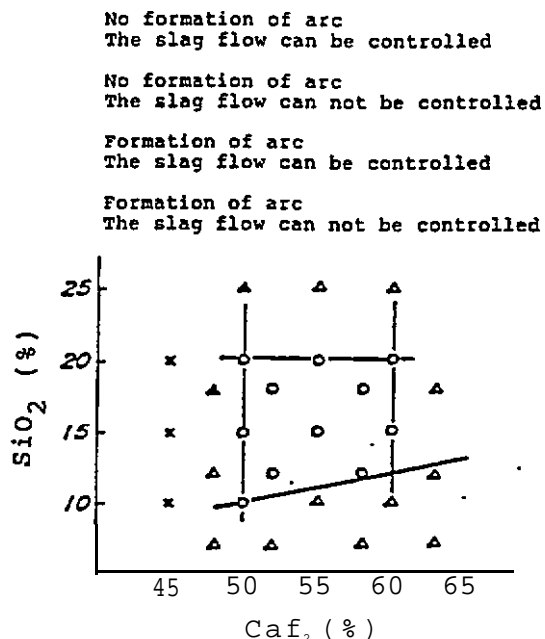


Fig. 13 Effect of CaF<sub>2</sub> and SiO<sub>2</sub> content on slag viscosity and process stability (25)

Fluxes can be either bonded or fused. The particle size of fluxes is generally controlled to 18/60 mesh, being smaller for SAS than for ESS (7). Because all fluxes are prone to moisture pick-up, they should be baked at 250-350°C (480-660°F) before using and held warm in the production area. Kawasaki claims that the ESS process is more tolerant of moisture pick up in the flux than the SAS process (6). However, the studies (28) have found that baking is necessary for the bonded fluxes because of their strong tendency to absorb moisture. Moisture in the flux induces porosity in the overlay, and this is especially severe when the alloy of the strip has a narrow temperature gap between its liquidus and solidus.

#### Strip Electrode Sizes

The thickness of the strip electrode is always expected to be thin enough to facilitate coiling into rolls, in order to conveniently feed cladding during ESS. The Japanese appear to have standardized the 0.4 mm (0.016 in.) thickness for all strip widths. This differs from the European practice where a 0.5 mm (0.02 in.) thickness is most common.

The ESS process favors the use of wide strip as long as the capacity of the power supply is adequate to provide 1000-2000 amps, typically. That is because, at a given layer thickness, the most marked effect of increasing the strip width is a decrease in dilution and penetration. Usually, the penetration of overlay deposits is always more accentuated at the sides of the bead. However, the relative importance of this localized higher penetration is lessened when (a) the strip width is increased, and (b) bead overlapping is considered (8). Strip widths of 75 mm (3 in.), 100 mm (4 in.), and 150 mm (6 in.) are most common in Japan; while widths of 60 mm (2.4 in.), 90 mm (3.5 in.), and 120 mm (4.8 in.) are more popular in Europe. In the U.S., through Sandvik Steel (7), a variety of strip electrodes are available commercially for ESS.

#### Voltage

Voltage is perhaps the most critical controlling parameter in the ESS process. In most ESS practice, the working range of voltage values is quite narrow, because of the shallow depth of the molten slag pool (5-10 mm [0.2-0.4 in]). Forsburg (7) reported that, for a fluoride-based flux, the stable range is usually 26-28 volts. When the voltage is below 24 volts, it is difficult to initiate the process, and the strip tends to stick to the base metal resulting in short circuiting. On the other hand, above 28 volts, the process starts arcing on the surface of the flux, and slag spatter becomes violent. Therefore, an accurate control in voltage is extremely important. Practices at the Oregon Graduate Center (28) found that the optimum voltage was closely related to the actual depth of the molten slag pool, and a stable ESS process could be performed at 22-24 volts. In addition, it was also shown (28) that an intentionally increased open-circuit voltage is beneficial to the initiation of ESS.

Even within the stable voltage range, fluctuations in voltage also affect the dilution, penetration and geometry of the surfacing layer as shown in Figure 14. By increasing voltage, the rising heat input increases the volume of base metal melted, thereby increasing the level of penetration and altering the geometry (width/thickness) of overlays. Nevertheless, the dilution level still remains essentially constant or only slightly decreases with increasing voltage.

#### Current

ESS has been reportedly used only with DC reverse polarity (electrode

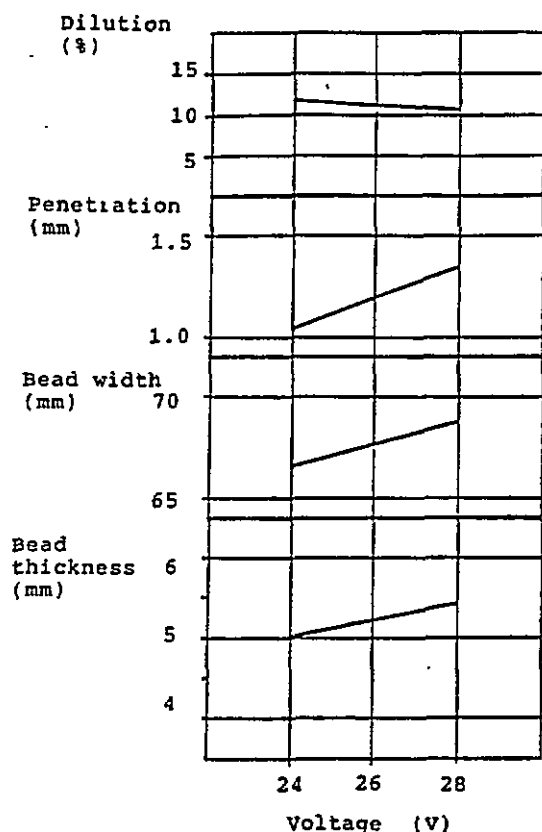


Fig. 14 Influence of voltage for strip electrode, size 60 x 0.5 mm at 1250A surfacing current and 150 mm/min travel speed (7)

positive). DC straight polarity results in an unstable operation at the normal working current density range for ESS, which is approximately twice that for the SAS process.

At a given voltage and surfacing speed, variations in the ESS current directly affects penetration, bead width and thickness, as shown in Figure 15. The dilution of surfacing layers is the result of two factors--the penetration into the base metal, and the thickness and width of the beads. Hence, the combined effects of both factors cancel each other, resulting in little change in the dilution.

Stable and quiet welding conditions can be achieved within a given range of ESS current. The optimum current density for strip ESS is around 40-45 A/mm<sup>2</sup> (26-29 kA/in<sup>2</sup>). At the higher values of current density, the amount of slag spatter increases and the depth of the slag pool has to be raised to stabilize the operation.

#### Travel Speed

At a given welding current and voltage, increasing the travel speed

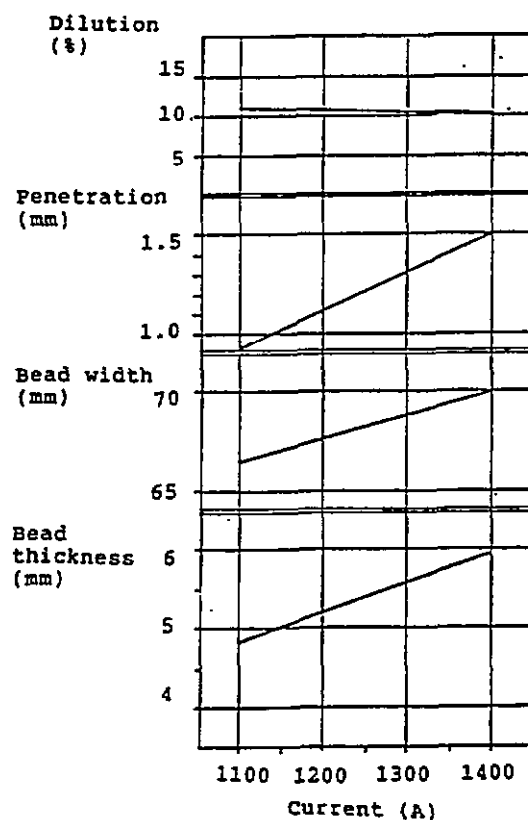


Fig. 15 Influence of current for strip electrode size 60 x 0.5 mm at 26V and 150 mm/min travel speed (7)

tends to increase dilution and penetration, while decreasing bead width and thickness, as shown in Figure 16. Increasing the travel speed in effect reduces the heat input and, thereby, decreases the electrical conductivity of slag. The ESS process can only be stable when sufficient contact area between the molten slag pool and the melting strip is maintained. An excessively fast surfacing speed may cause the strip to be in contact with cold flux or insufficiently heated slag, thus resulting in sporadic arcing and process instability.

In general, the travel speed should be optimized for both economy (fast speed) and an adequate thickness of surfacing layer (about 4-6 mm [z 0.2 in.]) (81). Excessive travel speed results in not only a bead thickness less than 4 mm, but also in the risk of the formation of undercutting. On the other hand, too slow a travel speed results in a bead thickness above 6 mm. Then, the wetting angles of beads become too steep and slag entrapment may occur at the overlaps. In general, the optimum travel speed range is about 160-200 mm/min (6-8 in/min), which results in about a 10% dilution level,

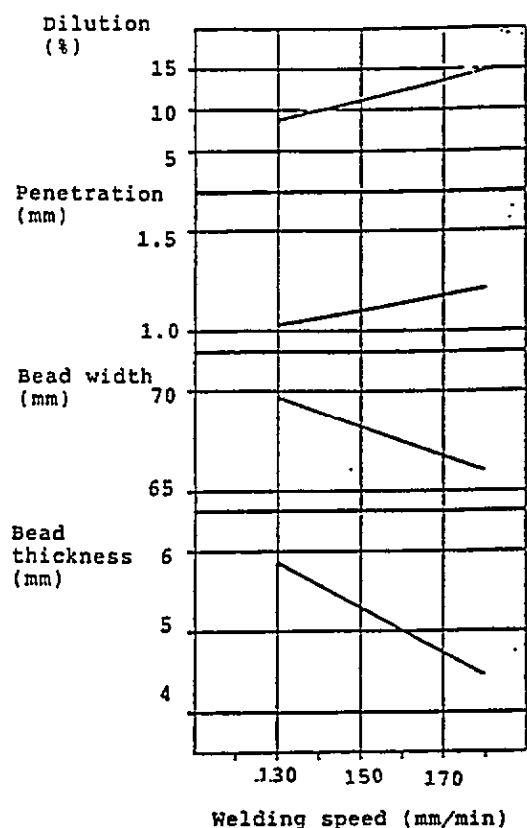


Fig. 16 Influence of travel speed for strip electrode 60 x 0.5 mm at 1250A and 26V (7)

and consumes about 0.15 kJ/mm<sup>2</sup> (96 kJ/in<sup>2</sup>) heat input (28).

#### Other ESS Parameters

The strip extension, i.e. the conventionally called "stick-cut" (the free length of the strip extending from the contact jaws to the slag pool), is not critical in this process. Usually it may vary from 25-40 mm (1-1.5 in) (7). However, the greater the strip extension, the greater will be the deposition rate for a given setting as in normal welding operations due to ohmic heating of the filler strip.

The depth of flux burden should just cover the strip extension or up to 5 mm over the extension length. Typical flux depth ranges from 30-45 mm (1.2-1.8 in) (7). If the flux is too shallow, arcing develops as the slag depth is less than the arc gap" for the given voltage and conduction through the slag is "open-circuited".

The limitation of parent metal thickness depends on the heat input during ESS and the width of strips used. Forsburg (7) reported that in order to ensure sound ESS with a 60 x 0.5 mm (2.4 x 0.02 in) strip, the

minimum parent metal thickness is 40 mm (1.6 in.). The minimum diameter of curved surface for ESS with the 60 x 0.5 mm strip electrodes is 250 mm (10 in.) for external surfacing, and 450 mm (18 in.) for internal surfacing. This is ideally suited for the rebuilding of ship propeller shafts. Practices at the Oregon Graduate Center (28) have found the above limitation was relatively conservative. For example, with a 60 x 0.5 mm strip, ESS could be performed on 25 mm (1 in.) thick plates.

#### QUALITY CONTROL

##### Stability of Process

Although economically desirable, the major problem associated with using a faster surfacing speed is the stability of the process. If the surfacing speed is excessive, the slag pool becomes cold and erratic submerged arcing will occur.

One possible way to avoid this trouble is to judiciously select an angle of inclination (downhill) for the base plate. This causes the molten slag and metal pool to flow slightly ahead of the strip, thus ensuring that the strip is in appreciable contact with the molten pool in spite of an increase in the surfacing speed.

The inclination angle of the parent metal also affects the dilution level of surfacing layers, as shown in Figure 17. It has been recognized that the downhill position slightly favors a decrease in dilution, which is sometimes important for the quality of microstructure of single pass deposits.

As mentioned above, the current and voltage of the ESS process can only vary within a narrow range. Maintaining optimum power parameters is very critical in order to continue a stable surfacing process. If disturbances in current or voltage can be monitored and recorded, a coefficient of stability could be used for quantitative determination, which has been used in the Soviet Union since 1962 (11,29).

The electrode inclination angle also influences the dilution, the width of bead and the thickness of overlay (7,8,10), as illustrated in Figures 18, 19 and 20. A greater electrode inclination angle (forehand) results in decreased dilution, wider bead and reduced thickness. In fact, the Japanese "HS" process (mentioned in the previous chapter) is based on this principle. When attempting to increase the surfacing speed for better economy, this geometrical parameter becomes extremely important. At a greater electrode angle, slag is pushed ahead of the electrode. Hence, care must be taken

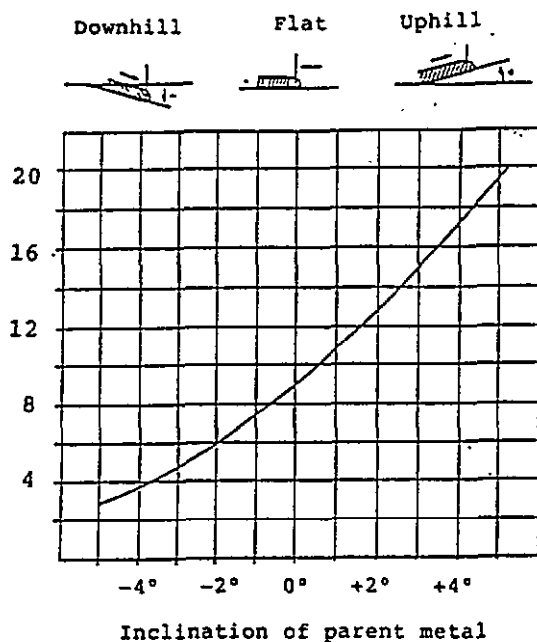


Fig. 17 Influence of inclination of base metal on dilution for strip electrode size 60 x 0.5 mm, 1250A, 26V and 140 mm/min travel speed (7)

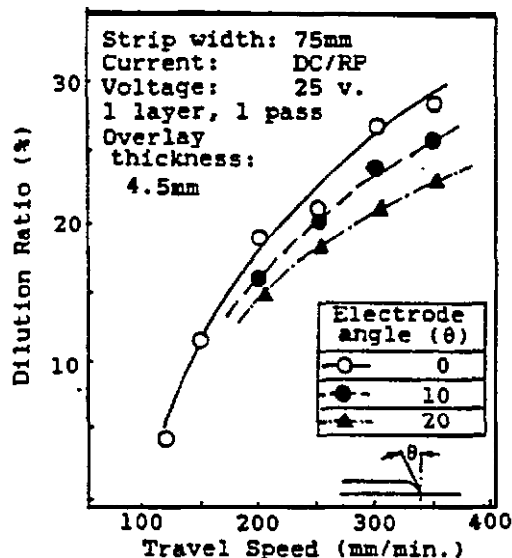


Fig. 18 Effect of travel speed on dilution (10)

when selecting the electrode angle, particularly when the curvature or the inclination angle of the parent metal is also being considered.

#### Residual Stresses

Surfacing stresses are principally induced by shrinkage of the overlay during solidification. These stresses may result in cracking, deformation,

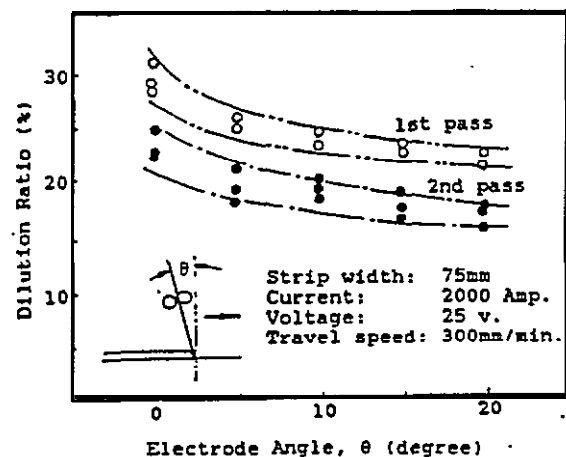


Fig. 19 Effect of electrode angle on dilution (10)

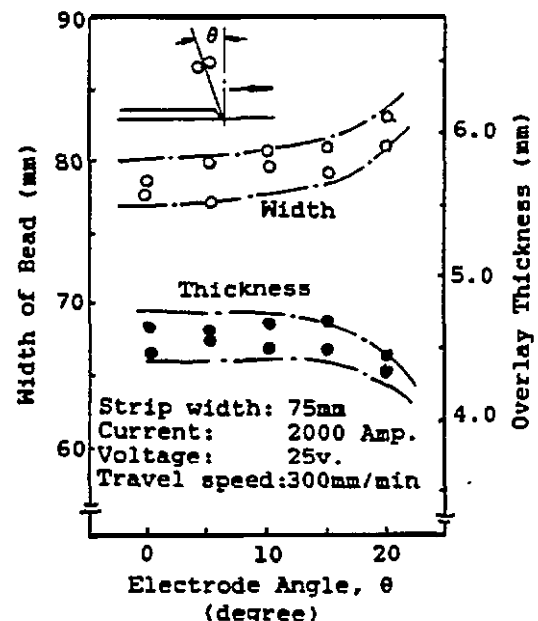


Fig. 20 Influence of electrode angle on the bead width and thickness (10)

disbonding and reduction in designed resistance to wear and corrosion, as summarized by Babiak (30,36).

The value of stress induced in the surfaced parts depends on the degree of solidification shrinkage, the difference in coefficient of thermal expansion between the filler metal and base metal, and the phase changes occurring in the surfacing materials. To simplify this complex problem, the residual stress developed in overlays can be classified in three categories:

- (1) Surfacing a massive part of soft steel with a nonhardening material. The surfacing layer and the

heat affected zone of the parent metal are stressed in high tension, whereas the parent metal in contact with the overlay is in compression (Figure 21). A good example of this case is the cladding of mild steels with a corrosion-resistant stainless steel coating.

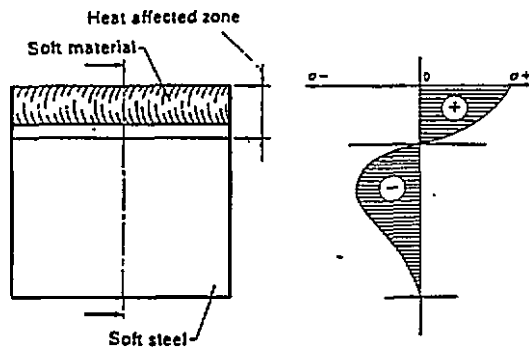


Fig. 21 Stresses in a component of low carbon steel alloy surfaced with a soft alloy (30)

- 12) Surfacing a mild steel with a hardenable states are just opposite to those of case 1 as shown in Figure 22. Here the surfacing layer is in compression while the base metal is in a tensile state of stress. This situation is common for some hardfaced parts.

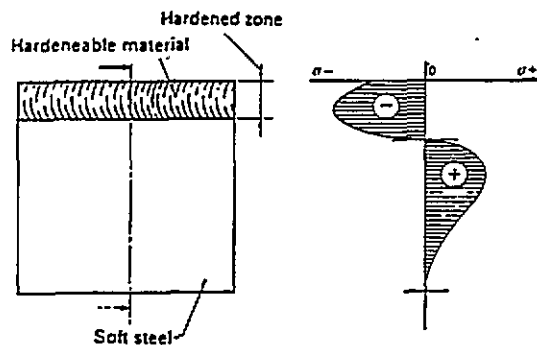


Fig. 22 Stresses in a component of mild steel surfaced with hardenable material (30)

- (3) Surfacing a hardenable steel with an austenitic alloy. The stress states can become very complicated (Figure 23). The surfacing layer is subjected to tensile state of stress. The hardened part of the heat affected zone is subjected to greater compressive stress. Below this hardened layer in the heat affected zone, tensile stresses

appear to be enhanced. In the part of parent metal farthest away from the surface overlay, the stress state becomes compressive once again.

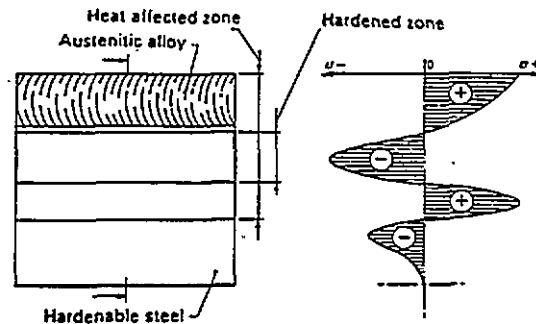


Fig. 23 Stresses in a component of hardenable steel surfaced with an austenitic alloy (30)

Blaskovic (13) reported measurements of stress in the ESS layers deposited by the dual strip method. It was shown that annealing (620°C/20hr + 650°C/10hr) eliminated the stress peak, but a tensile stress zone still remained.

The actual values of stresses depends on a variety of factors. Among them are the surfacing procedure, the consideration of the intermediate layer and the stress state of surfaced parts in service. To minimize the harmful residual stresses in surfaced work pieces, the following are recommended:

- 11) The proper selection of both the base metal and the filler strip materials to provide satisfactory metallurgical bonding and the desired chemical and mechanical properties;
- (2) The selection of process parameters, such as the travel speed, the heat input, and the number of passes to produce the required dilution, penetration and bead shape;
- (3) The possible application of an intermediate layer with transition chemical composition and properties having the strength and thermal expansion properties to buffer the undesirable metallurgical properties of a direct bond between filler metal and parent metal;
- (4) The cost-effective use of preheating for the parent metal only when necessary.

## Disbanding Problem

Since the surfacing process may involve depositing a layer of material having different chemical composition and mechanical properties (particularly the thermal expansion coefficient) than those of the parent metal, bonding strength between the overlay and the substrate becomes an important metallurgical consideration. This can be critical when surfaced parts are designed for special environments, such as elevated temperature or high hydrogen pressure.

For example, consider the surfacing of steel with the corrosion-resistant austenitic stainless steel. Depending on the  $Cr_{eq}/Ni_{eq}$  ratio of the deposited layer, a dual effect is noticed:

- (1) Austenite grains may coarsen at the fusion zone between deposited metal and the base metal. This coarse grained austenitic structure, being lower in strength, is susceptible to disbonding. Furthermore, for applications in severe chemical or nuclear environments, diffusion of hydrogen to the grain boundaries also produces a weakening of the fusion zone structure, which once again leads to disbonding (31). To avoid this, it is desirable to limit the austenitic grain coarsening to 0.5%. The coarse grain percentage is defined as the length of the austenite grain boundary, which is parallel to the fusion boundary, divided by the length of the fusion boundary. To achieve this, a  $Cr_{eq}/Ni_{eq}$  ratio of at least 1.85 is used, according to the Kawasaki Steel European patent, as shown in Figure 24 (31)

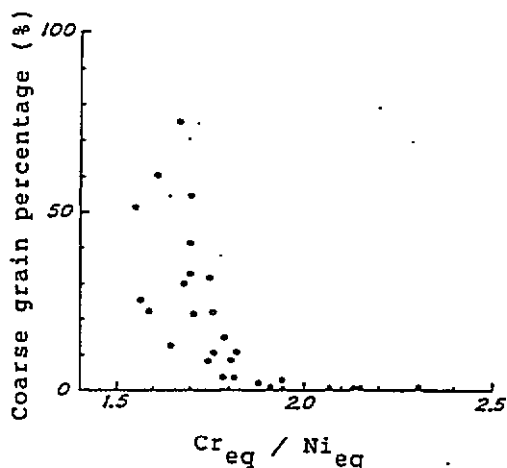


Fig. 24 Effect of  $Cr_{eq}/Ni_{eq}$  ratio on coarse grain percentage (31)

- (2) The percentage of delta ferrite present in the fusion zone is a function of the  $Cr_{eq}/Ni_{eq}$  ratio. Although, the presence of delta ferrite has a beneficial effect of preventing both hot cracking and precipitation of grain boundary carbides, it can also transform into the sigma phase at 500°C or above. The presence of the sigma phase leads to disbonding, as well. Thus, the acceptable level of the delta ferrite content is about 8 to 10%, and this is once again achieved by maintaining a Cr/Ni equivalent ratio of at least 1.85, as predicted by the standard Schaeffler diagram (31).

In Japan, a number of research projects were devoted to hydrogen-induced disbonding susceptibility in pressure vessels made of 2-1/4Cr-1Mo steel with an austenitic stainless steel overlay deposited by strip ESS. Tanaka (10) claimed that the Kobe Steel Ltd. HS process could improve the disbonding problem. This improved disbonding resistance was attained by a greater cooling rate and much finer grains near the interfaces. The HS process inhibited the development of coarser grains in the heat affected zone of the base metal, and might be effective in the prevention of under-clad cracking or cold cracking. The Japan Steel Works long-term studies (32-35) considered that the surfacing parameters hardly affected the disbonding resistance of surfaced parts. For example, austenitic/martensitic duplex structure provided the overlay layer with good disbonding resistance, which was obtained by modulating the process in a manner similar to the Kobe Steel "HS" process. They claimed the residual stress in the through-thickness direction at the bond between the first layer deposit and the base metal was smaller than that of the conventional ESS. The low residual stress provided an ESS technique that could produce overlays with good disbonding resistance.

## APPLICATIONS OF STRIP ESS

Presently, strip ESS is entirely foreign technology, which has further widened the construction cost gap between the Asian shipyards and U.S. shipbuilders. However, utilization of this foreign technology and the substantial improvements in strip ESS anticipated at the Oregon Graduate Center will enhance the economic position of U.S. shipyards to rebuild worn, eroded or redesigned structural ship components, such as large propeller shafts, rudder horns, strut shafts, deeply corroded portions of the hull, hawse pipes and leading edges of rudder castings.

This process, though fully automatic, is also portable in the shipyard when a conventional land inexpensive) carriage system is used to mobilize the strip ESS system in remote locations. A typical carriage system can handle 1500 amps and can pull power cables 30 m (100 ft.) long while being either track or manually guided. These carriage systems have been commercially manufactured in the United States for many years for Submerged arc welding applications, particularly in shipyards.

## CONCLUSIONS

Based on a computerized search of the international technical journals on the subject of electrosag surfacing, a critical review was performed and the following can be concluded:

1. ESS with strip electrodes is the most economical and productive method to overlay a wide variety of corrosion and/or wear resistant deposits on Structural ship components, such as propeller shafts.
2. The highest deposition rates combined with the lowest base metal dilution are characteristic of ESS with strip electrodes compared to conventional surfacing methods, such as strip SAS, GMAW and SMAW.
3. The dominant thick-section surfacing process in Japan, the Soviet Union and several European countries is ESS.
4. Neither U.S. shipyards nor U.S. manufacturing industries have adopted the ESS process. Conventional surfacing methods are still utilized in the U.S.
5. Technically, the key difference between the newly-developed ESS process and other similar processes, such as SAS and ESW, is the flux chemistry.

## ACKNOWLEDGMENT

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